Final Project Memorandum
South Central Climate Science Center Project

1. ADMINISTRATIVE

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Project Title:
Establishing a foundation for evaluating the ecological implications of climate change along a gradient in macroclimatic drivers of coastal wetland ecosystems

Date of Report:
22 January, 2016

Period of Performance:
June 2013 - December 2015

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$329,500

2. PUBLIC SUMMARY

The northern Gulf of Mexico coast spans a dramatic water availability gradient (precipitation range: 700 to 1800 mm/year) and represents an excellent natural laboratory for developing climate-influenced ecological models for natural resource managers and culture keepers. In this project, we used this zone of remarkable transition to develop macroclimate-based models for quantifying the regional responses of coastal wetland ecosystems to climate variation. In addition to providing important fish and wildlife habitat and supporting coastal food webs, these coastal wetlands provide many ecosystem goods and services including clean water, stable coastlines, food, recreational opportunities, and stored carbon. Our objective was to examine and forecast the effects of macroclimatic drivers on wetland ecosystem structure and function in the northern Gulf of Mexico. Our first major step in meeting this overall objective was to develop a quantitative understanding of the connections between climate and ecosystem structure. We then incorporated the resulting information into quantitative vulnerability assessments that examine sensitivity (via observed data), exposure (via alternative future climate scenarios), and adaptive capacity (via life history literature). In the process, we identified regional climate-ecological

thresholds for coastal wetland ecosystems. Our study focused on coastal wetland variations across relatively dramatic precipitation and temperature gradients in the northern Gulf of Mexico and included study areas in TX, LA, MS, AL, and FL. The project provided valuable experience and opportunities for five early-career researchers (one post-doctoral fellow, two current or recent undergraduate students, and two early-career research scientists).

3. TECHNICAL SUMMARY

Approximately 80% of the contiguous U.S.'s coastal wetlands are in the southeastern U.S. In addition to providing important fish and wildlife habitat and supporting coastal food webs, these coastal wetlands provide many ecosystem goods and services including clean water, stable coastlines, food, recreational opportunities, and stored carbon (Barbier et al. 2011, Engle 2011). Due to their position at the land-sea interface, coastal wetlands are vulnerable to future changing conditions (e.g., accelerated sea-level rise, freshwater availability reductions, winter climate change, coastal land use change), and natural resource managers and culture keepers are often asked the following two questions: *(1) How will climate change affect coastal wetlands and their ability to support fish and wildlife habitat and other important ecosystem goods and services?; and (2) How can we improve efforts to sustain the natural and cultural resources provided by coastal wetlands for current and future generations?*

Responding to these questions requires an understanding of the regional macroclimatic drivers that affect the structure and functioning of these ecosystems. Too often, an emphasis is placed solely on the effects of accelerated sea-level rise without investigating other simultaneous and interactive effects of climate change (e.g., freshwater availability and temperature change). The northern Gulf of Mexico spans a relatively dramatic macroclimatic transition zone that, in combination with a low-relief coastal topography, results in a high diversity and spatial coverage of coastal wetland ecosystem types. Ecologists have long noted that macroclimatic drivers regulate coastal wetland ecosystem types in this region (Copeland 1966, Longley 1994, Montagna et al. 2007). Coastal wetlands that receive sufficient rainfall and freshwater inputs often support highly-productive woody and/or herbaceous-dominated plant communities (e.g., mangrove forests, salt marshes, brackish marshes). However, where evaporation exceeds freshwater inputs, salts can become concentrated and produce hypersaline conditions that are inhospitable to wetland foundation plant species (e.g., salt pan, salt flat ecosystems; Ranwell 1972, Adam 1990, Pennings and Bertness 1999). Of the many plant species found globally, only a small number of species are able to survive and thrive in tidal saline wetland environments (e.g., marsh graminoids, succulents, and mangrove trees). These wetland plants have been called foundation species because of their important functional role; in physically-stressful tidal environments, foundation plant species create habitat, modulate ecosystem dynamics, and enable the development of highly-productive tidal wetland ecological communities (Dayton 1972, Bertness and Leonard 1997, Ellison et al. 2005, Angelini et al. 2011) that support coastal food webs, store carbon, provide important fish and wildlife habitat, improve water quality, and protect coastlines (Viosca 1928, Millenium Ecosystem Assessment 2005, Barbier et al. 2011).

The objective of this study was to examine and forecast the effects of macroclimatic drivers on wetland ecosystem structure and function in the northern Gulf of Mexico. Our first major step in meeting this overall objective was to develop a quantitative understanding of the connections between climate and ecosystem structure. We then incorporated the resulting information into quantitative vulnerability assessments that examine sensitivity (via observed data), exposure (via alternative future climate scenarios), and adaptive capacity (via life history literature). In the process, we identified regional climate-ecological thresholds for coastal wetland ecosystems. Our study focused on coastal wetland variations across relatively dramatic precipitation and temperature gradients in the northern Gulf of Mexico. Annual precipitation is low near the Mexico-U.S. border (700 mm/year), gradually increases across TX, and is relatively high in LA, MS, AL, and FL (up to 1800 mm/year). Winter severity also varies across this gradient (range of 30-year minimum temperatures: -9 to -15 ^{O}C from the Mexico-U.S. border to Alabama, respectively). Due to the important functional role that foundation species play in coastal wetlands, our research places an emphasis on macroclimatic effects upon foundation species presence, abundance, and structure, and the implication for ecosystem functioning.

To complete this research, we collected a combination of field and GIS-derived data in ten estuaries and five states (TX, LA, MS, AL, and FL). We worked with the following landowners/land managers (corresponding estuary in parentheses): (1) Lower Rio Grande Valley National Wildlife Refuge (Lower Laguna Madre, TX), (2) Laguna Atascosa National Wildlife Refuge (Lower Laguna Madre, TX), (3) King Ranch (Upper Laguna Madre, TX), (4) South Padre Island National Seashore (Upper Laguna Madre, TX), (5) Mustang Island State Park (Upper Laguna Madre, TX), (6) Mission Aransas National Estuarine Research Reserve and the Texas General Land Office (Mission Aransas Bay, TX), (7) Aransas National Wildlife Refuge (San Antonio Bay, TX), (8) Brazoria National Wildlife Refuge (Galveston Bay, TX), (9) Big Branch National Wildlife Refuge (Lake Ponchartrain, LA), (10) Grand Bay National Estuarine Research Reserve (Grand Bay, MS), (11) Weeks Bay National Estuarine Research Reserve (Weeks Bay, AL), (12) Hillsborough and Manatee Counties (Tampa Bay, FL), and (13) Ten Thousand Islands National Wildlife Refuge (Ten Thousand Islands, FL).

The data and metadata from this project have been archived on Science Base and, following a one-year publication period, will be available via this link:
https://www.sciencebase.gov/catalog/item/521cf699e4b01458f785805c

4. PURPOSE AND OBJECTIVES

The objective of this study was to examine and forecast the effects of macroclimatic drivers on wetland ecosystem structure and function along the northern Gulf of Mexico coast. Our first major step in meeting this overall objective was to use modeling to develop an understanding of the connections between climate and ecosystem structure. We then incorporated the resulting information into quantitative vulnerability assessments that examine sensitivity (via observed data), exposure (via alternative future climate scenarios), and adaptive capacity (via life history literature). In the process, we identified regional climate-ecological thresholds for coastal wetland ecosystems.

5. ORGANIZATION AND APPROACH

This work was conducted by a team of scientists from the U.S. Geological Survey's Wetland and Aquatic Research Center and the University of Houston. The paragraphs below identify the research methods utilized and activities performed.

Study areas and sampling design

We collected field data within ten estuaries that spanned the northern Gulf of Mexico coast. Estuaries were selected based upon their position along the ecologically-relevant winter temperature and precipitation gradients present within the region (Osland et al. 2013, Osland et al. 2014, Osland et al. 2016). The ten estuaries include Lower Laguna Madre (TX), Upper Laguna Madre (TX), Mission Aransas Bay (TX), San Antonio Bay (TX), Galveston Bay (TX), Lake Pontchartrain (LA), Grand Bay (MS), Weeks Bay (AL), Tampa Bay (FL), and Ten Thousand Islands (FL).

Within each estuary, we sampled along 6-8 transects (70 transects in total). We positioned transects so as to capture estuary-scale salinity and elevation gradients, as well as the representative vegetation zones observed within the tidal saline wetlands of a given estuary. All transects were oriented roughly perpendicularly to the shoreline.

For each transect, we employed a sampling protocol designed to capture the entire tidal saline wetland elevation gradient, as well as all the transitions between vegetative zones within tidal saline wetlands. We began each transect in open water and positioned 1-m^2 plots where we encountered at least one of the following three criteria: (1) a vegetation transition criterion (i.e., a clear transition zone or ecotone between two visibly different plant communities); (2) an elevation criterion (i.e., a 15-cm increase or decrease in elevation relative to the previous plot); or (3) a distance criterion (i.e., a horizontal movement of 20 m from the previous plot with neither a change in vegetation zone nor a 15-cm change in elevation). Where we met the elevation or distance criterion but not the vegetation criterion, we placed only one plot. Where we encountered a vegetation transition zone, we placed a total of three plots (i.e., one plot on the shoreward side of the transition, one plot at the center of the transition, and one plot on the landward side of the transition). The vegetation in plots located shoreward or landward of a transition zone was characteristic of its respective side of the ecotone, while the vegetation in the central plots contained an approximately equal mixture of plant communities from both sides of the transition zone. For abrupt transition zones, the central plots often had two halves dominated by different species. For diffuse transition zones, the central plots often contained a scattered mixture of the species present on either side of the transition zone. Where multiple vegetation transition zones were present within a small area (e.g., an area the size of one or two 1-m^2 plots), we placed multiple 1-m^2 plots side by side across the multiple transition zones. Finally, when we encountered conspicuous shifts in vegetation height or density, or in the composition of non-dominant species, we included additional 1-m^2 plots in order to characterize these changes.

We ended a transect when either: (1) the plot elevation exceeded two tidal ranges (i.e., two Great Diurnal Ranges) above mean lower low water; or (2) we moved two 20-m distance increments without encountering a vegetation transition zone or a 15-cm change in elevation (i.e., the distance criterion was used consecutively). Note that the goal of this design was not to accurately quantify and compare estuary-scale vegetation coverage, but rather to quantify abiotic-biotic linkages across relatively dramatic local and regional abiotic gradients. Within each estuary, we sampled a total of between 87 and 122 1-m^2 plots. For the entire study (i.e., across all ten estuaries), we sampled a total of 1020 1-m^2 plots.

Plant data

Within each 1-m^2 plot, we estimated the percentage of plant cover above and below 1.4 m separately for all species. We measured mean and maximum vegetation canopy heights, and recorded the species of the tallest individual present within each plot. We quantified light [i.e., photosynthetically active radiation (PAR)] interception in each plot using a linear ceptometer

(AccuPAR LP-80, Decagon Devices, Pullman, Washington, USA) (Whitbeck and Grace 2006). For short-statured vegetation (i.e., vegetation below the scientist's ability to record; < ~2 m), we measured light intensity at ground level and above the vegetation canopy. For tall-statured vegetation (e.g., forests), we measured light at ground level within the plot and at a height of 1.4 m outside the canopy in unobstructed sunlight. We calculated a proxy for standing aboveground plant biomass by multiplying the mean canopy height by the proportion of PAR intercepted. We used this simple biomass proxy to further quantify the variation in physical structure of vegetation across abiotic gradients.

Soil data
Within each 1-m^2 plot, a soil sample was collected to 15-cm depth using a custom-made stainless steel split-corer corer (4.7 cm diameter, split cylinder with a piano hinge) (Osland et al. 2012). While in the field, samples were stored in a cooler with ice packs. Upon return to the laboratory, samples were stored at 4 ºC until processing. In the laboratory, soils were dried at 60 °C to a constant mass, homogenized with a mortar and pestle, and sieved through a 2-mm screen. Samples were then further homogenized using a planetary mill (Frisch Pulviresette USA, New York, New York). Soil bulk density was determined as a simple dry weight to volume ratio (Blake and Hartge 1986). Soil moisture content was determined as a gravimetric wet-weight based concentration (i.e., water weight divided by weight of soil plus water). Soil organic matter was determined via loss on ignition in a muffle furnace at 475 ºC for 16 hours (Karam 1993, Wang et al. 2011).

Elevation data
The elevation (NAVD88) and horizontal position of each 1-m^2 plot were determined using a high-precision Global Navigation Satellite System (GNSS) (Trimble R8 and TSC3, Trimble, Sunnyvale, California, USA), in combination with real-time Continuously Operating Reference Station (CORS) networks where available (i.e., LSU's GULFNet network, Texas' TxDOT network). In addition to the field-based elevation measurements, we obtained plot-specific tidal datum estimates [specifically, mean higher high water (MHHW)] via the use of the National Oceanic and Atmospheric Administration's (NOAA) VDatum software tool version 3.1 (Parker 2003, Myers et al. 2005).

Climate data
We obtained climate data from various sources for the 30-year period extending from 1981-2010. For precipitation and temperature, we obtained continuous gridded climate data created by the PRISM Climate Group (Oregon State University; http://prism.oregonstate.edu) using the PRISM (Parameter-elevation Relationship on Independent Slopes Model) interpolation method (Daly et al. 2008). We used the PRISM gridded data to determine the 30-year mean annual precipitation (MAP) and the 30-year absolute minimum temperature (minT) (i.e., the coldest temperature recorded during the 30-year period) for each of our study plots. We also obtained aridity data and potential evapotranspiration data for each plot from the Global Aridity Index datasets (Trabucco and Zomer 2009).

6. PROJECT RESULTS
The primary project results to date are summarized via the subsequent four abstracts. These abstracts come from: (1) two manuscripts that have already been published; and (2) two

manuscripts that are under review. The publication portion of this memorandum provides links to these products.

Abstract from: Osland, M. J., N. Enwright, and C. L. Stagg. 2014. Freshwater availability and coastal wetland foundation species: ecological transitions along a rainfall gradient. *Ecology* 95:2789-2802.

Climate gradient-focused ecological research can provide a foundation for better understanding critical ecological transition points and nonlinear climate-ecological relationships, which is information that can be used to better understand, predict, and manage ecological responses to climate change. In this study, we examined the influence of freshwater availability upon the coverage of foundation plant species in coastal wetlands along a northwestern Gulf of Mexico rainfall gradient. Our research addresses the following three questions: (1) what are the region-scale relationships between measures of freshwater availability (e.g., rainfall, aridity, freshwater inflow, salinity) and the relative abundance of foundation plant species in tidal wetlands; (2) How vulnerable are foundation plant species in tidal wetlands to future changes in freshwater availability; and (3) What is the potential future relative abundance of tidal wetland foundation plant species under alternative climate change scenarios? We developed simple freshwater availability-based models to predict the relative abundance (i.e., coverage) of tidal wetland foundation plant species using climate data, estuarine freshwater inflow-focused data, and coastal wetland habitat data. Our results identify regional ecological thresholds and nonlinear relationships between measures of freshwater availability and the relative abundance of foundation plant species in tidal wetlands. In drier coastal zones, relatively small changes in rainfall could produce comparatively large landscape-scale changes in foundation plant species abundance which would affect some ecosystem good and services. Whereas a drier future would result in a decrease in the coverage of foundation plant species, a wetter future would result in an increase in foundation plant species coverage. In many ways, the freshwater-dependent coastal wetland ecological transitions we observed are analogous to those present in dryland terrestrial ecosystems.

Abstract from: Osland, M. J., N. M. Enwright, R. H. Day, C. A. Gabler, C. L. Stagg, and J. B. Grace. 2016. Beyond just sea-level rise: considering macroclimatic drivers within coastal wetland vulnerability assessments to climate change. *Global Change Biology* 22:1-11.

Due to their position at the land-sea interface, coastal wetlands are vulnerable to many aspects of climate change. However, climate change vulnerability assessments for coastal wetlands generally focus solely on sea-level rise without considering the effects of other facets of climate change. Across the globe and in all ecosystems, macroclimatic drivers (e.g., temperature and rainfall regimes) greatly influence ecosystem structure and function. Macroclimatic drivers have been the focus of climate-change related threat evaluations for terrestrial ecosystems, but largely ignored for coastal wetlands. In some coastal wetlands, changing macroclimatic conditions are expected to result in foundation plant species replacement, which would affect the supply of certain ecosystem goods and services and could affect ecosystem resilience. As examples, we highlight several ecological transition zones where small changes in macroclimatic conditions would result in comparatively large changes in coastal wetland ecosystem structure and function. Our intent in this communication is not to minimize the importance of sea-level rise. Rather, our overarching aim is to illustrate the need to also consider macroclimatic drivers within vulnerability assessments for coastal wetlands.

Abstract from: Gabler, C.A., Osland, M.J., Grace, J.B., Stagg, C.L., Day, R.H., Hartley, S.B., Enwright, N.M., From, A.S., McCoy, M.L. & McLeod, J.L. *In review*. Macroclimatic change expected to transform coastal wetland ecosystems this century. *Submitted to Nature Climate Change.*

Coastal wetlands, existing at the interface between land and sea, are highly vulnerable to climatic and other global changes. Macroclimate (temperature and precipitation regimes) greatly influences coastal wetland ecosystem structure and function globally. However, research on climate change impacts in coastal wetlands has concentrated primarily on sea-level rise and largely ignored macroclimatic drivers, despite their power to transform plant community structure (e.g., marsh-to-mangrove conversions or vegetated-unvegetated transitions) and thus the ecosystem services provided. Here we model wetland plant community structure based on macroclimate using field data collected across the northern Gulf of Mexico coast along broad temperature and precipitation gradients. Our analyses reveal strongly nonlinear temperature thresholds regulating the potential for marsh-to-mangrove conversion, and also precipitation thresholds for dominance by various functional groups. Based on current and projected climatic conditions, we demonstrate that transformative ecological changes are probable throughout the region, even under conservative climate scenarios. Coastal wetland ecosystems are functionally similar worldwide, so changes in this region are indicative of potential future changes globally.

Abstract from: Osland, M.J., Day, R.H., Lee, C.T., Brumfield, M.D., Dugas, J.L. & Jones, W.R. *In review*. Spatial and temporal patterns of mangrove expansion and contraction at a poleward range limit. *Submitted to Global Ecology and Biogeography.*

Within the context of climate change, there is a pressing need to better understand the ecological implications of changes in the frequency and intensity of climate extremes. Along subtropical coasts, warmer and less frequent freeze events are expected to permit freeze-sensitive mangrove forests to expand poleward and displace freeze-tolerant salt marshes. Here our aim was to better understand the drivers of poleward mangrove migration by quantifying spatiotemporal patterns in mangrove range expansion and contraction across land-ocean temperature gradients. We worked within a freeze-sensitive mangrove-marsh transition zone that spans a land-ocean temperature gradient in one of world's most wetland-rich regions (Mississippi River Deltaic Plain; Louisiana, USA). We used historical air temperature data (1893-2014), alternative future climate scenarios, and coastal wetland coverage data (1979-2011) to quantify spatiotemporal oscillations and climate-wetland linkages. Our analyses indicate that in the past 121 years, mangrove range expansion and contraction has occurred across land-ocean temperature gradients, and that these oscillations have been controlled primarily by extreme freeze events (i.e., air temperatures below a threshold zone of -6.3 to -7.6 °C). Mangrove resistance, resilience, and dominance were all highest in areas far from land where temperature extremes were buffered by large expanses of water and saturated soil. Under climate change, these areas will likely serve as local hotspots for mangrove dispersal, growth, range expansion, and displacement of salt marsh. Our findings show that the frequency and intensity of freeze events across land-ocean temperature gradients greatly influence spatiotemporal patterns of range expansion and

contraction of freeze-sensitive mangroves. We expect that, along subtropical coasts, similar processes govern the distribution and abundance of other freeze-sensitive organisms. In broad terms, our findings can be used to better understand and anticipate the ecological effects of changing winter climate extremes, especially within the transition zone between tropical and temperate climates.

7. ANALYSIS AND FINDINGS

The primary project analyses and findings to date are summarized via the subsequent four abstracts. These abstracts, which have also been included in the Project Results section, come from: (1) two manuscripts that have already been published; and (2) two manuscripts that are under review. The publication portion of this memorandum provides links to these products.

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8. CONCLUSIONS AND RECOMMENDATIONS

Primary Conclusions:

- Climate gradient-focused ecological research can provide a foundation for better understanding critical ecological transition points and nonlinear climate-ecological relationships, which is information that can be used to better understand, predict, and manage ecological responses to climate change. We examined the influence of freshwater availability upon the coverage of foundation plant species in coastal wetlands along a northwestern Gulf of Mexico rainfall gradient. Our research addressed the following three questions: (1) what are the region-scale relationships between measures of freshwater availability (e.g., rainfall, aridity, freshwater inflow, salinity) and the relative abundance of foundation plant species in tidal wetlands; (2) how vulnerable are foundation plant species in tidal wetlands to future changes in freshwater availability; and (3) what is the potential future relative abundance of tidal wetland foundation plant species under alternative climate change scenarios? We developed simple freshwater availability-based models to predict the relative abundance (i.e., coverage) of tidal wetland foundation plant species using climate data, estuarine freshwater inflow-focused data, and coastal wetland habitat data. Our results identify regional ecological thresholds and nonlinear relationships between measures of freshwater availability and the relative abundance of foundation plant species in tidal wetlands. In drier coastal zones, relatively small changes in rainfall could produce comparatively large landscape-scale changes in foundation plant species abundance which would affect some ecosystem good and services. Whereas a drier future would result in a decrease in the coverage of foundation plant species, a wetter future would result in an increase in foundation plant species coverage. In many ways, the freshwater-dependent coastal wetland ecological transitions we observed are analogous to those present in dryland terrestrial ecosystems.
- Due to their position at the land-sea interface, coastal wetlands are vulnerable to many aspects of climate change. However, climate change vulnerability assessments for coastal wetlands generally focus solely on sea-level rise without considering the effects of other facets of climate change. Across the globe and in all ecosystems, macroclimatic drivers (e.g., temperature and rainfall regimes) greatly influence ecosystem structure and function. Macroclimatic drivers have been the focus of climate-change related threat evaluations for

terrestrial ecosystems, but largely ignored for coastal wetlands. In some coastal wetlands, changing macroclimatic conditions are expected to result in foundation plant species replacement, which would affect the supply of certain ecosystem goods and services and could affect ecosystem resilience. As examples, we highlight several ecological transition zones where small changes in macroclimatic conditions would result in comparatively large changes in coastal wetland ecosystem structure and function. Our intent in this communication is not to minimize the importance of sea-level rise. Rather, our overarching aim is to illustrate the need to also consider macroclimatic drivers within vulnerability assessments for coastal wetlands.

- We modeled wetland plant community structure based on macroclimate using field data collected across the northern Gulf of Mexico coast along broad temperature and precipitation gradients. Our analyses reveal strongly nonlinear temperature thresholds regulating the potential for marsh-to-mangrove conversion, and also precipitation thresholds for dominance by various functional groups. Based on current and projected climatic conditions, we demonstrate that transformative ecological changes are probable throughout the region, even under conservative climate scenarios.
- Within the context of climate change, there is a pressing need to better understand the ecological implications of changes in the frequency and intensity of climate extremes. Along subtropical coasts, warmer and less frequent freeze events are expected to permit freeze-sensitive mangrove forests to expand poleward and displace freeze-tolerant salt marshes. Here our aim was to better understand the drivers of poleward mangrove migration by quantifying spatiotemporal patterns in mangrove range expansion and contraction across land-ocean temperature gradients. We worked within a freeze-sensitive mangrove-marsh transition zone that spans a land-ocean temperature gradient in one of world's most wetland-rich regions (Mississippi River Deltaic Plain; Louisiana, USA). We used historical air temperature data (1893-2014), alternative future climate scenarios, and coastal wetland coverage data (1979-2011) to quantify spatiotemporal oscillations and climate-wetland linkages. Our analyses indicate that in the past 121 years, mangrove range expansion and contraction has occurred across land-ocean temperature gradients, and that these oscillations have been controlled primarily by extreme freeze events (i.e., air temperatures below a threshold zone of -6.3 to -7.6 °C). Mangrove resistance, resilience, and dominance were all highest in areas far from land where temperature extremes were buffered by large expanses of water and saturated soil. Under climate change, these areas will likely serve as local hotspots for mangrove dispersal, growth, range expansion, and displacement of salt marsh. Our findings show that the frequency and intensity of freeze events across land-ocean temperature gradients greatly influence spatiotemporal patterns of range expansion and contraction of freeze-sensitive mangroves. We expect that, along subtropical coasts, similar processes govern the distribution and abundance of other freeze-sensitive organisms. In broad terms, our findings can be used to better understand and anticipate the ecological effects of changing winter climate extremes, especially within the transition zone between tropical and temperate climates.

Primary Recommendations

- Along the northern Gulf of Mexico coast, macroclimatic drivers greatly influence coastal wetland ecosystem structure, function, and the provision of ecosystem goods and services. The effects of changing macroclimatic conditions should be incorporated into future-focused models and conservation planning efforts. The region has multiple “zones of instability.” These are zones where small changes in climate or freshwater management can result in landscape-scale changes in coastal wetland ecosystem structure and function. Within these “zones of instability”, additional research and monitoring is needed to improve of our understanding of the potential implications of climate change-induced ecological regime shifts for important ecosystem goods and services.

- One of the primary challenges facing coastal wetland scientists today is the improved understanding and prediction of the response of coastal wetlands to sea-level rise and other aspects of global change. Much of the research to date within this arena has focused on salt marsh grasses and has not incorporated the effects of macroclimatic drivers. There is a need for longer-term experimentation and research that will contribute to our understanding and ability to predict the implications of changes in foundation species structure and composition upon ecological processes that will enable coastal wetlands to keep pace with sea-level rise, migrate inland, and continue to provide important ecosystem services in the future.
- Although mangroves, salt marshes, and salt flats are often treated by scientists and land managers as entirely different ecosystems, there is much to gain from considering these systems together via a holistic lens. In the context of climate change, broad perspectives are needed, and scientists and environmental managers should consider the possibility that, in addition to being converted to open water or migrating vertically or horizontally in response to accelerated sea-level rise, their local wetland could be dominated by an entirely different foundation species and/or functional group in response to changing macroclimatic conditions.

9. OUTREACH

The outreach products included below are separated into the following two categories: (1) Publications; and (2) Presentations. The presentations category includes webinars, conference presentations, workshop presentations, and seminars.

Publications

Osland, M. J., N. Enwright, and C. L. Stagg. 2014. Freshwater availability and coastal wetland foundation species: ecological transitions along a rainfall gradient. *Ecology* 95:2789-2802. http://onlinelibrary.wiley.com/doi/10.1890/13-1269.1/abstract

Osland, M. J., N. M. Enwright, R. H. Day, C. A. Gabler, C. L. Stagg, and J. B. Grace. 2016. Beyond just sea-level rise: considering macroclimatic drivers within coastal wetland vulnerability assessments to climate change. *Global Change Biology* 22:1-11. http://onlinelibrary.wiley.com/doi/10.1111/gcb.13084/abstract

Lovelock, C.E., Krauss, K.W., Osland, M.J., Reef, R. & Ball, M.C. (In press) The physiology of mangrove trees with changing climate. Tropical tree physiology: adaptations and responses in a changing environment (eds G.H. Goldstein & L.S. Santiago), pp. to be determined. Springer, New York, New York, USA. http://www.springer.com/us/book/9783319274201

Gabler, C.A., Osland, M.J., Grace, J.B., Stagg, C.L., Day, R.H., Hartley, S.B., Enwright, N.M., From, A.S., McCoy, M.L. & McLeod, J.L. *In review*. Macroclimatic change expected to transform coastal wetland ecosystems this century. *Submitted to Nature Climate Change.*

Osland, M.J., Day, R.H., Lee, C.T., Brumfield, M.D., Dugas, J.L. & Jones, W.R. *In review*. Spatial and temporal patterns of mangrove expansion and contraction at a poleward range limit. *Submitted to Global Ecology and Biogeography.*

Presentations

Osland M.J. 2013. Regional climate variability and coastal wetland foundation species. Webinar for the Gulf Coast Vulnerability Assessment.

Yando E.S., M.W. Hester, K.W. Krauss, R.H. Day, M.J. Osland. 2013. The belowground implications of mangrove forest migration: plant-soil variability across forest structural gradients in TX, LA, and FL. Texas Mangrove Research Symposium, Mission Aransas National Estuarine Reserve.

Osland M.J., N. Enwright, R.H. Day, T.W. Doyle. 2013. Winter climate change and coastal wetland foundation species: salt marshes vs. mangrove forests. Texas Mangrove Research Symposium, Mission Aransas National Estuarine Reserve.

Osland M.J., E.S. Yando, R.H. Day, J. Larriviere, A.S. From, M. Dupuis, K.W. Krauss, J.W. Willis, M.W. Hester. 2013. A comparison of salt marsh-mangrove ecotones in the northern Gulf of Mexico: above and belowground variability across structural gradients. Society of Wetland Scientists [Withdrew presentation due to federal travel restrictions]

Yando E.S., M.J. Osland, J.W. Willis, R.H. Day, K.W. Krauss, M.W. Hester. 2013. Mangrove structural gradients: A comparison of plant-soil interactions across saltmarsh-mangrove ecotones. Society of Wetland Scientists, South Central Chapter.

Osland M.J., Enwright N., R.H. Day, C.L. Stagg. 2013. Macroclimatic drivers of tidal wetland ecosystems along the Gulf of Mexico coast. Grand Bay National Estuarine Research Reserve Research Symposium.

Yando E.S., M.J. Osland, J.W. Willis, R.H. Day, K.W. Krauss, M.W. Hester. 2013. Salt marsh-mangrove ecotones in the Northern Gulf of Mexico: a comparison of plant-soil variability across structural gradients. Coastal and Estuarine Research Federation.

Osland M.J., Day R.H., Enwright N., Doyle T.W., Stagg C.L. 2013. Climate change and tidal wetland foundation species: thresholds, resilience, and alternative stable states in the northern Gulf of Mexico. Coastal and Estuarine Research Federation.

Day R.H., M.J. Osland, J. Larriviere, A.S. From. 2013. An allometric equation for estimating aboveground biomass of black mangrove (*Avicennia germinans* (L.) L.) shrubs in the northern Gulf of Mexico. Coastal and Estuarine Research Federation.

Osland M.J., Enwright N., Day R.H., Doyle T.W. 2014. Winter climate change and coastal wetland foundation species: salt marshes vs. mangrove forests. Poster for Southeast Climate Science Center Grand Opening.

Osland M.J. 2014. Climate change and coastal wetland foundation species: mangroves, marshes, and salt flats. Invited seminar for Texas A&M Galveston's Marine Biology Seminar Series.

Osland, M.J. 2014. From restoration to climate change: the ecological effects and drivers of mangrove expansion into salt marsh. Invited seminar for the University of South Florida Department of Integrative Biology's Seminar Series.

Hundy L.C., M.J. Osland, J.M. Willis, R.H. Day, M.W. Hester. 2014. Effect of elevation and soil properties on black mangrove (*Avicennia germinans*) survival and growth in a created tidal saline wetland. State of the Coast: 3rd Biennial Conference of the Coalition to Restore Coastal Louisiana.

Yando E.S., M.J. Osland, J.W. Willis, R.H. Day, K.W. Krauss, M.W. Hester. 2014. Salt marsh-mangrove structural gradients: Implications for restoration within a shifting ecotone in Louisiana and across the Northern Gulf of Mexico. State of the Coast: 3rd Biennial Conference of the Coalition to Restore Coastal Louisiana.

Gabler C.A., M.J. Osland, J.B. Grace, C.L. Stagg, R.H. Day, S.B. Hartley, N. Enwright, A.S. From. 2014. Macroclimatic controls on tidal wetland ecosystems: Variation in foundation plant community zonation across abiotic gradients in three northern Gulf of Mexico estuaries. Texas Bays and Estuaries Meeting.

Osland M.J., Day R.H., Enwright N., Stagg C.L. 2014. Beyond sea-level rise: incorporating climate into coastal wetland vulnerability assessments. State of the Coast: 3rd Biennial Conference of the Coalition to Restore Coastal Louisiana.

Osland M.J. 2014. Beyond just sea-level rise: incorporating climate into coastal wetland vulnerability assessments. Webinar for the South Atlantic Landscape Conservation Cooperative Third Thursday Web Forum.

Yando E.S., M.J. Osland, M.W. Hester. 2014. Micro-spatial examination of above- and belowground processes at the salt marsh-mangrove ecotone in the northern Gulf of Mexico. Joint Aquatic Sciences Meeting.

Osland M.J. and R.H. Day. 2014. Mangrove restoration and migration in a changing climate: climatic drivers and shifting ecotones. Conference on Ecological and Ecosystem Restoration.

Osland M.J. 2014. Beyond just sea-level rise: incorporating climate into coastal wetland vulnerability assessments. Webinar for Gulf of Mexico Alliance Federal Working Group.

Osland M.J., N. Enwright, K. Griffith, A. From, S. Hartley. 2014. Landward wetland migration under future sea-level rise and urbanization. Landscape Conservation Cooperative- South Central Climate Science Center- Louisiana State University Partnership Meeting.

Gabler C.A., M.J. Osland, J.B. Grace, C.L. Stagg, R.H. Day, S.B. Hartley, N. Enwright, A.S. From. 2014. Macroclimatic controls on tidal wetland ecosystems: Variation in foundation plant community zonation across abiotic gradients in three northern Gulf of Mexico estuaries. Ecological Society of America.

Osland M.J. 2014. Beyond just sea-level rise: incorporating climate into coastal wetland vulnerability assessments. Florida Adapts: Fish and Wildlife Commission Education Lunch 'N' Learn Series.

Gabler, C.A. 2014. Climates change, environments fluctuate and niches shift: Finding order and opportunity in ecological variability. Southern Illinois University.

Yando E.S., M.J. Osland, J.W. Willis, R.H. Day, K.W. Krauss, M.W. Hester. 2014. Heterogeneity in plant ecological interactions at a shifting salt marsh-mangrove ecotone in the northern Gulf of Mexico. Society for Wetland Scientist- South Central Chapter.

Osland M.J. 2014. Landscape scale assessments of climate impacts to Gulf of Mexico coastal wetlands. National Workshop on Large Landscape Conservation.

Yando E.S., M.J. Osland, J.W. Willis, R.H. Day, K.W. Krauss, M.W. Hester. 2014. Mangrove forests vs. salt marshes: the ecological implications of climate-induced woody plant encroachment on plant-soil interactions in tidal saline wetlands. Webinar hosted by Gulf Coastal Plains and Ozarks Landscape Conservation Cooperative and the Southeast Climate Science Center.

Osland M.J. 2014. Climate change and coastal wetlands: ecological transitions along the Gulf of Mexico coast. Plenary speaker presentation for the Gulf Estuarine Research Society, Coastal and Estuarine Research Federation.

Hanisko, M.W., Gray, W., Kidwell, D., Laursen, K., Osland, M., Sempler, S., Swann, L.D., Tirpak, J., Wilder, S., Woodrey, M. 2014. NOAA Sentinel Site Program: activities and recent accomplishments of the northern Gulf of Mexico Sentinel Site Cooperative: Alabama-Mississippi Bays and Bayous Symposium.

Brumfield, M, Osland, M.J., Day, R.H. 2015. Mangrove livelihood and extreme weather events. American Meteorological Society.

Gabler, C.A., Osland, M.J., Grace, J.B., Stagg, C.L., Day, R.H., Hartley, S.B., Enwright, N., From, A.S., McLemore, M.L., McLeod, J. 2015. Macroclimatic controls on tidal wetland ecosystems: Variation in plant community structure across climatic gradients in northern Gulf of Mexico estuaries. Texas Bays and Estuaries.

Gabler, C.A. 2015. Climates change, environments fluctuate, and niches shift: finding order and opportunity in ecological variability. Texas A&M – Corpus Christi.

Hundy, L.G., Osland, M.J., Willis, J.M., Day, R.H., Hester, M.W. 2015. Abiotic controls of black mangrove (*Avicennia germinans*) survival and growth in a restored Louisiana coastal wetland. Society of Wetland Scientists.

Gabler, C.A. 2015. Climates change, environments fluctuate, and niches shift: finding order and opportunity in ecological variability. Sam Houston University.

Gabler, C.A., Osland, M.J., Grace, J.B., Stagg, C.L., Day, R.H., Hartley, S.B., Enwright, N., From, A.S., McLemore, M.L., McLeod, J. 2015. Macroclimatic controls on tidal wetland ecosystems: Variation in plant community structure across climatic gradients in northern Gulf of Mexico estuaries. Ecological Society of America.

Osland, M.J., Day, R.H., Lee, C.T., Brumfield, M.D., Dugas, J.L. & Jones, W.R. 2015. Black mangrove forest resistance and resilience to winter climate extremes: implications for range expansion under climate change. Ecological Society of America.

Gabler, C.A. 2015. Climates change, environments fluctuate, and niches shift: finding order and opportunity in ecological variability. University of Texas, Rio Grande Valley.

Osland, M.J. 2015. Climate change and coastal wetlands- ecological transitions across the northern Gulf of Mexico. Louisiana State University.

Osland, M.J., Day, R.H., Lee, C.T., Brumfield, M.D., Dugas, J.L. & Jones, W.R. 2015. Mangroves vs. salt marshes in Louisiana: resistance, resilience, and the implications for climate-induced range expansion. Coastal and Estuarine Research Federation.

DISCLAIMER

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